Studies for Students.

AGENCIES WHICH TRANSPORT MATERIALS ON THE EARTH'S SURFACE.[1]

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When account is taken of all the foregoing considerations touching the character of the drift, the character of the rock surface which underlies it, and the relation of these to each other, we are able to exclude as principal agents of the drift, many of those forces which transport materials on the earth's surface. The agencies prominently concerned in shifting loose materials are wind, water and ice. Other agencies of extreme violence, such as earthquakings and volcanic explosions, occasionally affect small areas. Suddenly and locally they accomplish very considerable results in the way of shifting material from one point to another. The direct action of gravity, too, by producing landslides and by carrying loosened masses of rock down steep slopes effects much in the way of transfer of surface materials. But we have no warrant for believing that any or all these agencies can move such materials as those of the drift

[1] The sequel to the articles which appeared under the heading *Studies for Students*, Vol. II. Nos. 7 and 8.

through any such distances as the drift has been carried. On the contrary, we have the best of reasons for believing that they could not.

WIND.

The strongest winds are able to carry no more than very small pebbles along with the sand and dust which make up their chief load. Transportation of the drift by the wind is therefore impossible. Locally the wind has moved the sand of the drift, heaping it into dunes or spreading it with more uniformity over surfaces which it did originally occupy. But although the wind may have played a part in the deposition of the great body of material included under the term drift, either at the time of its origin or since, it can have been no more than a very subordinate factor. The work of the wind, so far as the great body of drift is concerned, can be looked upon as nothing more than incidental. There remain to be seriously considered, therefore, only two agencies, ice and water.

WATER.

Next to the wind, moving water is by far the most widely active agent which is now shifting material on the earth's surface. The countless streams, large and small, the waves and currents of the thousands of lakes, as well as those of the seas, are constantly moving those materials which come within their reach, and do not exceed their power. Streams, waves and currents, do each their appropriate work. The results have much in common, yet each has its diagnostic marks.

Streams. Streams sometimes carry heavy burdens of earthy material. If the velocity of a stream be great, and particularly if its gradient be high, it is able to roll along stones of considerable size. The torrents which course down hillsides after violent showers sometimes carry blocks of stone weighing hundreds of pounds. If the high velocity of the transporting stream were to be constantly maintained, great quantities of coarse material might thus be carried down in the long process of time. The presence of coarse material, even bowlders of some size, is

therefore no proof that the deposit containing them was not made by a stream.

The transportation of coarse materials by streams may be facilitated by the co-operation of ice. When the rigors of winter are past, and the snows upon the hills and mountains are being rapidly melted, the swollen streams break up the ice which has imprisoned them, and hurry the broken masses forward with their increasing floods. As these masses of ice are torn away from the banks of the streams, they sometimes carry with them very considerable quantities of earth, sand, gravel and even bowlders, to which the ice had frozen. These materials are deposited at some point further down the stream, or in the lake or sea to which the river flows.

But however we may conceive the work of rivers to be abetted, the material which they transport could never be deposited on land surfaces outside the limits of their valleys. It might be distributed widely by the waves and currents of the seas and lakes into which the rivers carried it, but it could never be deposited on the tops of hills or mountains. Furthermore, the deposits made by streams, except in the case of alluvial cones, have surfaces which are nearly plane. They are never marked by such hills and depressions as often characterize the drift. The difference is not one of degree, but one of kind. However vigorously we may suppose streams to have acted, therefore, and however we may suppose their proper work to have been modified by co-operating agencies, they fail to account for the distribution of the drift or for its topography; and not only do they fail to account for the distribution and topography of the drift, but its distribution and topography are such as to constitute positive and conclusive evidence against the reference of the larger part of the drift to rivers acting under any circumstances whatever. Since the distribution of the drift disproves all hypotheses which ascribe it to rivers, the argument need not be pursued further. But if we were to examine in detail each of the characteristics of the drift with reference to its production by streams, we should find that their combined testimony is

not only negatively but positively overwhelming against the notion that the bulk of the drift can be accounted for by any phase of river work of any degree of intensity assisted by any other agent in a subordinate capacity. Streams, then, were not the principal agencies concerned in the deposition of the drift, though nothing here said is to be construed to mean that they did not play a subordinate part. The fact that stratified drift frequently extends much further south in valleys than on the adjacent uplands suggests that rivers may have played a subordinate rôle in the transportation and deposition of the drift.

Materials deposited by streams along their valleys are properly called "river drift." Generally speaking, river drift is so unlike the general sheet of drift under consideration, both in its inherent character and in its relations, that the one is not likely to be mistaken for the other. Yet the range of variation, both in the drift and in river drift, is great. When the variations are toward a common limit, as is sometimes the case, the one may closely simulate the other. But this does not appear to be true of any considerable body of the two types of drift, extending over any considerable area. Torrential deposits, such as are formed at the bases of steep mountain slopes, or along the valleys of streams which have high gradients, may closely resemble the drift so far as their physical constitution is concerned. But the distribution of such deposits, the shapes of their constituent stones, and their freedom from striation and planation, are generally sufficient to betray their origin. Lithologically, too, torrential deposits contain only materials which might have been gathered from the drainage basin of the stream concerned, while the constituents of the drift are rarely so limited in their range. If the materials entering into the constitution of torrential deposits were derived from the drift, and not greatly modified in the process of reworking, the resemblance of these deposits to the drift, and especially to the stratified drift, might be very close. Even in this case their distribution and structure might be decisive. Furthermore, if the existence of the drift must be presupposed in order to account for torrential deposits

which might be mistaken for the drift, it is clear that we have in the torrents no explanation of the drift itself.

Lakes and seas. By their waves and currents lakes and seas effect extensive transportation. Along the bases of steep cliffs storm waves sometimes have sufficient strength to move loose masses of rock many tons in weight. But bowlders so large as those common to the drift cannot be moved by the water of lakes or seas except along shores where waves are violent. Even along shores subject to strong waves, great bowlders cannot suffer extensive transportation at the hands of waves and currents. Even where the movements of the water are competent to transport them, they are worn out, or at any rate greatly reduced in size, before being carried far. Yet some of the huge bowlders of the drift have journeyed scores and even hundreds of miles, and that over regions where there is not only an absence of evidence that shores existed, but where, on the contrary, there is the best of evidence that shores did not exist during the time of drift formation, and where there is the best of evidence that seas or lakes have not existed since that time. Neither sea nor lakes can be responsible for their present position.

Again, deposits made by seas and lakes are composed of materials which are well assorted and stratified. The larger part of the drift is neither assorted nor stratified. Deposits made by seas and lakes contain relics of the plant and animal life which inhabited them while the deposits were making. The great body of the drift is devoid of lacustrine and marine fossils. In certain restricted localities, however, the drift contains marine fossils and in certain other restricted localities lacustrine fossils. The significance of these exceptions will be noted later. In spite of them the statement remains true that marine and lacustrine fossils are generally absent from the great body of the drift. It is hardly necessary to state that where the drift is made up in part of rock which contains fossils, these fossils reappear in the drift. Such fossils have no significance except in showing what formations contributed to the drift of the localities where the fossils exist.

Deposits made by standing water are necessarily restricted in

their vertical range. They cannot extend above the level reached by the crests of the highest waves, and in great thickness they cannot extend below the depths reached effectively by the bottoms of the waves. Although small amounts of fine sediment may be carried far out into lakes or into the sea, especially along the courses of currents, yet considerable deposits of lacustrine or marine sediments coarser than fine clay must be confined to a narrow belt of shallow water along the shores. Even within this belt there is a systematic gradation of material on the basis of size, the coarser being left nearer the shore, while only the finer reaches the outer part of the zone of abundant deposition.

If the level of the standing water along whose shores deposits are made varies, the shore deposits made at successive stages will have a corresponding vertical range. The deposits making at any given time must have an essentially horizontal upper limit, corresponding approximately with the level of the water. The earth's surface parts are known to be undergoing differential vertical movements, and are known to have suffered such movements in the past. It follows that shore deposits, horizontal in position at the time they were made, may not always remain so. But if they fail to preserve their original horizontal position, they can never assume any new position except such as might be given them by crustal movements.

No lake and no combination of lakes could cover the area which the drift covers. The only body of water which could have been everywhere where the drift is, is the sea. If the sea covered the whole of this area, including its mountains, and if the land gradually rose, or the sea receded, all parts of the drift area would have found themselves, sooner or later, at the level of the sea. In this way only could all parts of the drift-covered area have been affected by those parts of the sea along which, and along which only, abundant deposition of coarse materials can take place, if water alone be concerned.

To account for the absence of drift from the southeastern part of the United States, lower on the whole than the drift-covered territory to the north, it would be necessary to suppose that this

area was high at the same time that the drift area was submerged, if the sea was concerned as a principal agent in the origin of the drift. Such a supposition, if made, would have to be made not only without supporting evidence, but in the face of abundant and positive adverse evidence. If anything further need be said in refutation of the violent hypothesis referred to above, reference might be made to the position and relations of the line which marks the southern terminus of the drift. It will be remembered that this line is far from horizontal. Not only this, but it is a line which could not have been deformed from a horizontal position by post-drift warping. Without inquiring whence the sea could have derived material for such coarse deposits as the drift, in case the whole of the drift-covered territory was submerged, such extensive transportation of coarse material as the drift demonstrates could not have taken place at the hands of water alone.

Thus from the cursory examination of a few of its characteristics it is seen not only that lakes and seas, unaided by other agencies, fail to account for the drift, but that the drift bears in itself and in its relations, positive and conclusive testimony against the suggestion of its genesis at the hands of lakes or sea, acting as principal agents. The nature and the arrangement of the striæ on the rock beneath the drift would alone disprove its origin at the hands of any body of standing water. Were each feature of the drift, and each feature of the underlying rock examined in detail with reference to the possibility of its origin at the hands of standing water as principal agent, the combined testimony of all would be found to be overwhelming against the notion of such an origin.

If seas and lakes were not principal factors in the production of the drift as a whole, it does not follow that they were not subordinate factors, or that locally they were not of great importance.

WATER AND ICE CO-OPERATING.

Shore-ice or pan-ice co-operating with the water of lakes and seas.—It has already been seen that streams, even when aided by the ice which forms upon their surfaces in winter, cannot account

for the drift. It has been seen that lakes could never have covered the drift-mantled country, and therefore that the drift did not originate wholly or mainly through the agency of lakes. It has also been seen that the sea, acting alone, cannot account for the drift and its accompanying phenomena. It remains to inquire whether standing water, aided by the ice which forms, or which under favorable conditions may have formed on its surface, can account for the phenomena which water alone cannot explain. Since the distribution of the drift proves that it is not of lacustrine origin, and since lake ice is restricted to lakes, it is clear that lake ice cannot afford the key to the explanation of the drift. Yet because the action of the lake ice is more familiar than that of sea ice, it will be profitable to study it briefly.

The ice which forms upon the surface of lakes in winter may be subject to considerable movement both during the winter and in the spring. On fresh water, ice forms at a temperature of 32° Fahr. The ice thickens as the isothermal plane of 32° sinks beneath the surface. Although water expands on becoming ice, the ice cannot suffer reduction of temperature without contraction. If its temperature be lowered greatly, and that suddenly, as often happens in winter, the contraction of the ice is correspondingly great. The ice cover which fits a lake snugly at a temperature of 32° becomes too small, after contraction, to cover the whole surface of the water. It must either draw away from the shores, or crack. If the attachment of the ice to the shore is stronger than the cohesion of adjacent parts of the ice, the ice will crack. Otherwise it will draw away from the shore. Both withdrawal from the shore and cracking might take place in the same lake at the same time. The intense cold of the winter nights in temperate latitudes affords abundant illustration of both results. In whichever way they are formed, the breaches caused by the contraction of the ice will be healed by the freezing of the water which rises in them, and again the cover of ice fits snugly over the water beneath. When the temperature again rises, the ice expands. It was already large enough to cover the water, and expansion makes it too large. It therefore crowds the

shores of the lake and tends to advance upon them. Some part of the strain may be relieved by the arching of the ice, but this could not do away with shoreward pressure. Under favorable conditions, the shoreward movement may be considerable. When the shoreward movement of the ice begins, its margin may be frozen to stones of greater or less size. As it crowds upon the shore, the stones frozen to its lower surface will grind the surface over which it moves. If this surface be of material capable of receiving striæ, as limestone, it may be striated as the bowlder-bearing ice is shoved over it. Taken singly, the striæ thus produced may closely resemble those found in association with the drift. At the same time, the stones which marked the bedrock would themselves be worn after the fashion of the stones of the drift. The process of ice movement here described may be repeated many times in the course of a single season.

At the close of winter, fed by the swollen currents of streams flooded by melting snows, the water in the lakes rises. The melting ice is broken into blocks. In the flooded condition of the lakes, these blocks are carried above and beyond the usual shore lines. Waves may drive them still further. Where the slopes of the shore are gentle, and the waves high, the ice may be driven many feet above the high-water shore line, and many rods beyond it. In this movement, those blocks of ice which were originally frozen to the shore sometimes carry stony materials in their bases, and, thus armed, wear the surface over which they are shoved. The ice is sometimes broken up and driven on shore during the winter as well as in the spring. Once on the shore, the ice blocks may be frozen to the land surface, to be again moved inland by the waves and crowding ice blocks of succeeding storms and floods. While it seems altogether possible that striæ may be produced both on the bedrock and on loose stones by the shoreward movement of lake ice, good examples of striæ demonstrably thus produced, and comparable to those affecting the surface of the rock beneath the drift, are not known. The vertical range of such striæ would be very limited at best, unless the level of the lake changed.

Sea water freezes at a temperature of about 28° Fahr. With respect to temperature, sea water ice is believed to behave like other ice. Although ice never covers the sea from shore to shore, except in narrow bays, fjords, etc., belts of ice of considerable width are formed on its surface in high latitudes. This ice is sometimes broken up during the violent storms of winter, and uniformly suffers this fate in the storms of spring. Thus arise blocks or "pans" of floating ice, some of which are many acres in extent. These blocks of floating ice, frozen together in larger or smaller numbers, constitute the ice-floe of the northern seas. The ice of the sea is subject to all the movements which affect the ice of lakes, and to such additional movements as the tides may bring about. Since the waves of the sea are stronger than the waves of lakes, the ice of the sea may be correspondingly more effective in wearing its shores.

The striæ produced at any given period by pan-ice or ice-floe, must be confined to the shores. As developed at any one period of time, their vertical range must be exceedingly small, and the altitude at which they occur should nearly correspond at all points about the margin of any body of water on the shores of which they are formed. A great vertical range might conceivably be given to shore-ice or pan-ice striæ, if the water level was inconstant in relation to the land. If the land along shore were to rise gradually a thousand feet, or if the sea were to fall an equal amount, it can be conceived that shore-ice might produce striæ throughout the whole vertical range between the first and last water levels, if all conditions were favorable. But even on the most liberal interpretation possible, this conception does not at all meet the case of the striæ which are associated with our drift. Not to speak of other difficulties, the systematic arrangement of these striæ (see Vol. II., p. 849) is altogether fatal to the idea that ice along any shore, or along any combination of shores, was the principal agent concerned in their production.

If it be conceived that the whole area of land covered by drift was beneath the sea during the drift period, every part of the land surface, as it emerged, must at some time have been a sea

margin. Under such circumstances, if it be assumed that the temperature was low enough to freeze the sea water to considerable depths, the shore-ice might have done all that shore-ice can ever do in the way of developing striæ. But even with so violent an assumption, the direction of the striæ would be likely to betray their origin. Striæ formed in this way would be more or less nearly perpendicular to the line of the shore on which they were formed. On the slopes of isolated elevations, as they passed through the insular stage during emergence, the striæ formed by shore-ice should run up and down the slopes on all sides. The same would be true on the slopes of mountain ranges. The striæ would thus be developed in a sort of system, a system determined by the method and position of their formation. The waves, striking the shores at different angles might seriously interfere with the regularity of the development of the system. The striæ associated with the drift are arranged systematically, but the principle underlying their arrangement is radically different from that here stated. Taken as a whole, they do not stand in any definite relationship to any existent body of water, or to any body of water which can be conceived to have existed in the past.

While therefore shore-ice may be conceived to produce striæ simulating those beneath the drift, and while certain violent assumptions, if admitted, might enable us to conceive of a widespread development of these striæ, it is still true that such ice could never have produced any considerable part of the striæ accompanying our drift. Even if this were not true, the drift possesses numerous characteristics which would make its reference to shore-ice impossible, and it fails to possess numerous other characteristics which would certainly belong to it had any phase of shore-ice been the principal agent of its production. For example, if shore-ice were the agent of the drift, the great body of it should be stratified, since it was deposited mainly in water. However effectively the action of shore and floating ice might have destroyed the superficial stratification along successive shore lines, it could not have destroyed it to any considerable depth. Again, the constitution of the drift, and the distance and

direction of its transportation, are altogether conclusive against any such conception of its origin. Shore-ice could not account for the wide transportation of the drift, since shore-ice does little more than shove about, through short distances, such materials as are already at hand. It does not transport them in quantity, widely. The topographic distribution of the drift, too, seems to put insuperable difficulties in the way of the pan-ice theory. It does not follow that standing water and shore-ice have played no part in the production of the drift because they cannot be looked upon as the principal agents concerned.

Icebergs. Icebergs emanate from glaciers. They may float out upon any lake or sea to which glaciers descend, and they may distribute themselves as widely as the conditions of temperature, wind, and water movements allow. They may carry such stony materials as the glaciers from which they originated were possessed of. This they may distribute as widely as they are drifted. We have now to enquire whether icebergs, conjointly with the water of lakes and seas, could produce the drift of the North American and European continents.

Icebergs cannot float beyond the limit of the lakes and seas on which their movements are dependent. The drift which they distribute cannot extend beyond these limits, and may fail by varying amounts, to reach them. These limits are vertical as well as horizontal. Berg drift can cover no lands which were not covered by the seas or lakes into which glaciers calved the bergs. The distribution of the existing drift by icebergs presents essentially the same difficulties, from the topographic standpoint, as its distribution by the sea. From the areal standpoint, the difficulties seem at first less overwhelming, since the southern and western limits of the drift might be thought to correspond with the geographic limits to which icebergs floated. On this hypothesis, the outer limit of the drift should be ill-defined, since very few bergs would reach the limit attained by those which went farthest. The distribution of icebergs today makes this point clear. If the drift were deposited by bergs, it should become thinner and thinner with increasing distance from its

source. If its border were anywhere marked by heavy accumulations, it should be where special topographic relations limited the movement of abundant bergs.

The border of the drift is often ill-defined, but it does not feather out to any such extent as this hypothesis would demand. The border is also frequently well defined, being marked by heavy beds of drift, and this where there is nothing in the topography or topographic relations to occasion local accumulation by means of icebergs.

When specific features of the drift, or other specific phenomena accompanying it, are examined, they are found to afford significant testimony touching the iceberg hypothesis of the drift. If it be inquired whether icebergs could striate the surface on which their drift lies, it may be answered that this could be done to a very limited extent only. An iceberg could not striate bedrock, so long as it was floating. When and where it grounded, it might produce markings upon its bed, but these could hardly be continuous for great distances. Neither would they be straight as a general rule. Bergs are likely to swerve as they ground, and any striæ they might produce would correspond with the direction of this swerving motion. Striæ believed to have been made by icebergs have been seen in a few localities, possessing the characteristics which might have been anticipated.

To be brought into existence by icebergs, the divergent systems of striæ observed beneath the drift would demand an impossible system of atmospheric or aqueous currents. Reference need only be made to the figure (Vol. II., p. 849) showing the arrangement of striæ in eastern Wisconsin. No system of air or water currents could drive the icebergs in such directions as to produce this remarkable system of striæ. Much less could there be systems of air or water currents which would occasion the repetition of the general features of this system many times within the area of drift. Icebergs would also be altogether incompetent to account for the production of striæ in many of the anomalous positions in which they occur, such as the under-

sides of overhanging cliffs, in horizontal grooves in vertical or sloping faces.

Except where icebergs grounded, any deposits they might make would be made through water. They should be largely stratified, although the type of stratification developed by the dropping of coarse and fine material through still water might be recognizably different from that developed in deposits made along shores or by running water. The type of stratification which affects the larger part of the stratified drift, is the stratification developed by rapidly moving streams. It is not the type of stratification which would be developed in material dropped through still water. Further, the relations which subsist between the stratified and the unstratified drift are not such as would exist if the drift were the work of icebergs. Were there no other insuperable difficulties in the way of supposing that icebergs were responsible for the drift, we should find it in the constitution of the drift. It will be remembered that the agents which deposited the drift at any given point, were generally agents which had gathered material all along a somewhat extended course, and that in general the larger part of the material which they left at any given point had been derived from sources close at hand. This is just the work which icebergs cannot do. They can carry such material as they possessed when they set sail, but they can gather nothing along the course of their journey.

Furthermore, if the whole of the drift-covered country were submerged, as must needs be if icebergs alone are to explain the drift, where was the land which nourished the glaciers whence the icebergs came?

From these considerations it seems certain that icebergs were not the sole or the principal agents of the drift. Were all the characteristics of the drift and all the phenomena accompanying it examined in detail, the result of their combined testimony would confirm the conclusions to which this partial examination has led. This would still remain true, even though certain features of the drift might seem to find adequate explanation in the icebergs. Since icebergs were not the sole or the principal agents

concerned in the production of the drift, it does not follow that they may not have played a subordinate part.

Neither winds, nor streams, nor lakes and seas, acting alone, can account for the drift. Neither can their combined activities, attributing to each its maximum, go far toward explaining the remarkable series of phenomena bound up in the drift, or closely associated with it. Even if shore-ice, pan-ice, and icebergs be added, the whole combination falls far short of adequacy, though pan-ice and icebergs might account for some phenomena which water and wind cannot. It is evident therefore that some other agency must have been concerned in the production of the drift, though wind and water and shore-ice and icebergs may have played subordinate rôles.

GLACIERS.

A possible agent concerned in the production of the drift is glacier ice. If glacier ice be responsible in whole or in part for the drift which has so great a development in North America and Europe, the study of the results effected by glacier ice to-day should give us confirmatory testimony. It is well known that many existing glaciers increase and diminish sensibly within periods of a few years. Even seasonal fluctuations in size are readily observed. These fluctuations of accessible glaciers facilitate the study of their work, and the careful study of the results which existing glaciers effect, affords a means of testing the possibility of the glacier origin of the drift.

After a glacier has retreated for a distance up the valley which it occupies, an area which was formerly covered by the ice is left bare. The area from which the ice has withdrawn is readily accessible, and the effects of former ice occupancy and activity may be seen. In such situations, the surface is found to be more or less generally covered with a mixture of bowlders, gravel, sand and clay. If many valleys occupied by glaciers be examined, these various constituents of the surface material may be found to co-exist in all proportions. They may be in approximately equal quantities in one valley, or in one part of one

valley, while any one may predominate over all the others elsewhere. In its physical heterogeneity therefore, this stony glacial débris very closely resembles certain common phases of our continental drift. In the glacier deposits of mountain valleys, however, stony material is likely to be more abundant relatively than in our drift.

If the stones of the drift in glacier valleys be examined, a considerable variety of rock types may sometimes be found. The glacier deposits are thus seen to possess lithological, as well as physical, heterogeneity. This is a second point of correspondence between glacier deposits and the drift. If the stones in glacier deposits be studied in connection with the surrounding rock formations which are *in situ*, it is found that the stony material deposited at the foot of any particular glacier corresponds with the types of rock found along the course of the valley through which the ice has come, and further, that pieces of all types of rock represented in the course of the valley through which the ice has come, are liable to be found in the deposits left by the ice on the surface from which it has withdrawn. But in general, the lithological heterogeneity in the deposits of existing glaciers is less extreme than in our drift.

In the glacier deposits, the various constituents, ranging from huge bowlders to fine clay, may often be seen mingled together without trace of stratification, just as in our drift. But stratified deposits are by no means wanting. Beds of assorted sand and gravel may sometimes be seen to overlie unstratified mixtures of bowlders, gravel, and clay in some places, and to underlie similar materials in others. Beds of stratified material may even be inserted between beds of unstratified. In all these characteristics and relations the deposits of the glaciers resemble those of the drift.

Many of the stones of the unstratified glacier deposits possess the subangular forms, and the planed and beveled surfaces which have been noted as characterizing the stones of our drift. The stony material of the stratified drift associated with glaciers is more commonly rounded. Some of the stones left by the glacier,

especially those having subangular forms and beveled faces, are found to be superficially marked with a series of parallel lines, or with multiple series of parallel lines, each series being discordant with each other. These surface markings appear to be identical with those on the stones of our drift. As in our drift, striated stones are less common in the stratified deposits associated with glaciers, than in the unstratified.

Upon careful examination, the fine earth (clay) in which the bowlders are imbedded, is found to consist of nothing more or less than fresh particles of rock, such as might be produced by crushing or grinding the stony matter of the same deposit into fine particles. In this respect also, deposits known to be of glacier origin find close correspondence with the drift. In the glacier deposits, too, the fine material which often serves as a matrix for the imbedded bowlders may sometimes be seen to be foliated, after the fashion of the corresponding material of the drift.

The topography of the deposits made by the glaciers is similar in kind to that which characterizes much of the drift as we know it, but is developed on a less extensive scale. Except in the axes of the glacial valleys the deposits are seen to stop on a descending slope where the ice stops, or where the ice has stopped at some earlier time, leaving the higher part of the valley drift-covered, and the lower part drift-free. Along the axes of the valleys, the deposits of gravel, sand, and silt have a nearly plane surface, and extend beyond (below) the unstratified drift.

The glacier deposits stand in the same relation to the underlying rock that our drift does. Where surfaces of bare rock are exposed to observation they may be seen to be polished and striated, the striæ being parallel with each other, and with the course of the valley down which the ice has moved. Upon the most careful examination, these striations on the rock recently occupied by alpine glaciers are found to be indistinguishable from those on the rock beneath the drift in the drift-covered areas of North America and Europe. If the rock of the valley bottom be laid bare by removing the drift, its surface is seen to be firm and fresh. Any decomposed material which may once have covered it has

been swept away, as well as all that part of the rock which had been affected by the disrupting and decomposing effects of surface exposure. In all these respects, the correspondence between the deposits made by glacier ice and the drift seems complete.

So too, if knobs or bosses of rock, large or small, chance to be discovered by the retreat of the ice, they may be seen to possess the form of *roches moutonnées*, with one side worn more than the others, and that the side facing up the valley. Now and then the striæ affecting the surface of these *roches moutonnées* may be seen to be deflected from their normal course down the valley, and to be bent round the bosses, showing that the elevation influenced the details of the movement which made the striæ, without turning the striating agent out of its general course.

It is sometimes possible to go back a short distance beneath the ice itself. The many caves made by natural and human agencies afford such opportunity. Under the ice one may often be fortunate enough to see the contact of the glacier with its bed. Under favorable circumstances the lower part of the ice may be seen to be set with stones and with other materials of all grades of coarseness and fineness. The movement of the rock-shod ice is too slow to be sensible, but it is easy to see that if it move at all, no matter how slowly, it must powerfully corrade its bed. At the same time that the bed of the glacier is striated and polished, the stones in the bottom of the ice, themselves the graving tools, will suffer wear similar to that which they inflict. Not only this, but if the different parts of the ice move at different rates the stones will rub one another during the movement. As they rub against one another, or as they rub against the bed over which the ice is moving, flat surfaces as well as striations will be developed. If for any reason the stones turn in their ice-setting, as when they encounter a resistant object in the rock-bed, they may expose a new surface to planation and striation, or the old surface may be lined in a new direction, thus developing a second set of striations crossing the first. If any particular stone is turned frequently enough and rubbed hard enough against its neighbors, or against the glacier's bed, successive sets of striæ may be effaced.

Those which finally remain, when the ice has deposited its load, will be only those which were last named, or those which escaped destruction. As successive sets of striæ on drift stones are obliterated, new ones taking their places, the stones become smaller. If the process be continued long enough, a stone may be completely worn out. The product of the wear would be rock-flour. Rock-flour, the product of glacial grinding, is carried on beneath the ice, and constitutes an earthy or clayey matrix, in which the accompanying stones and bowlders are imbedded. It is identical with the "clay" in which the bowlders are seen to be imbedded on the land from which the ice has receded. It is comparable in all respects to the matrix of our bowlder-bearing clays.

If one is fortunate enough to go beneath the ice at the point where a stream issues, it may be seen that the stream, even while its course is beneath the ice, is carrying such material as its velocity enables it to transport, and that it is continually dropping parts of its load. The deposits made by flowing water beneath the ice are stratified, as the deposits of running water always are. Should the ice crowd out over the stream's bed, as is possible, displacing the water in the operation, such parts of the stratified deposits as were not ground up and borne away by the ice might be buried beneath the unstratified deposits which it might make. Since this process of change may be repeated, ice succeeding water, and water ice, at any given point, we discover at least one way in which alternations of stratified and unstratified deposits may be brought about in connection with glacier ice.

The flowing water beneath the ice does not stop with the terminus of the glacier itself, but issues as a swift river, hurrying on down the valley, with such load of sediment as it can carry. These materials are spread out in alluvial plains beyond the edge of the ice, wherever the stream is unable to carry them further. Considerable plains of stratified material have been built up in this way by the ice-born rivers, beyond the ends of many alpine glaciers. In some cases they extend many miles down the valleys, the coarser materials being near the ice and the finer further away. In every essential particular concerning constitu-

tion, structure, form and relationship, these valley plains resemble the many valley deposits of stratified drift, which stretch beyond the unstratified drift in our own country and northern Europe.

All these considerations make it clear that there are many points in common between the deposits made by alpine glaciers, and the drift of the continental areas. Indeed, the correspondences between the two formations are so close, so numerous, and comprehend so many phenomena related to one another in intimate and nicely adjusted ways, that it is difficult to see how they could have been brought into existence by any other than identical agençies.

The physical heterogeneity of glacier deposits considered in relation to the sources whence their materials were derived; the lithological heterogeneity of these deposits likewise considered in relation to the sources whence the materials came; the sizes, shapes, and marking of the coarser parts of these deposits; the physical and chemical condition of their finer parts; the stratified, unstratified, and foliated structures of the various parts of these deposits in their relations to one another and to topography; the relation of these deposits to the rock upon which they rest; the frequent termination of the unstratified parts on declining surfaces; the extension of the stratified parts far down the valleys beyond the unstratified parts; the topographic relations of these deposits and their own topography; the systematically disposed striæ on the rock beneath them, taken in connection with the direction in which materials have been transported; the shapes of the hills worn by glaciers, and the relation of these forms to other associated phenomena; the general surface expression of the region worked over by a glacier, in contrast with adjacent regions which have been so affected; all these phenomena, so peculiar, so distinctive, and particularly all these phenomena in their manifold, and intricate, and peculiar, and nicely adjusted relations, afford a remarkable series of criteria for the recognition of glacier deposits, even in regions which now possess no remnant of ice.

The various marks left by glacier ice on the bed over which

it has moved are so many and so distinctive, and stand in such nicely adjusted relations to one another, that it hardly seems credible that any second agency or combination of agencies could produce results so similar as to be mistaken for them, if all the foregoing characteristics and relations are clearly developed and open to observation. It is not to be understood that all the marks of glacier deposits, or all the phenomena accompanying them, are always present at every point, or within any circumscribed area where glacier ice has been. The study of considerable areas of glacier deposits may sometimes be necessary for the recognition of all the features and relations referred to. Some, or even many of them may altogether fail of development in a given locality. Those which are developed may be but feeble. In a limited area of drift where relations are not discernible, or where many of the various characteristics referred to above are but poorly developed, or where they are not open to observation, glacier deposits might be confused with those produced by certain other agencies, especially if the region in question be one where glacier ice is not known to have been. If a glacier deposit be very ancient, it may have lost, by decay, most of its diagnostic characteristics; or, since its origin, it may have suffered alteration, with the effacement of its distinctively glacial marks, at the hands of some geological agent other than ice. It is not to be understood, therefore, that glacier deposits can always and everywhere be recognized at sight, especially in a region where glaciers do not exist, and where they are not known to have existed. But it is confidently believed that any series of typically developed glacial deposits which have suffered so little change that they still preserve the characteristics which the ice impressed upon them, cannot fail to give evidence of their origin, if their characteristics and relations are open to observation.

If glacier ice alone be responsible for the drift, it is necessary to suppose that the whole of the drift-covered area was overspread by an ice-sheet. Alpine glaciers are so small and so connected with mountains, that studying them alone, it seems

incredible, at first, that any extension of such glaciers could be great enough to account for the drift deposits of so great areas as those of North America and Europe. Fortunately, our knowledge of glaciers and of glacial phenomena is not restricted to Switzerland, or even to the type of glaciers which has been termed alpine. Larger bodies of land ice exist in various parts of the world. The largest of these which has received even a small amount of attention is the ice cap of Greenland. But this is accessible only with difficulty, and has received little attention compared to that which has been bestowed on many mountain glaciers. While, therefore, the Greenland ice-sheet might afford a closer analogy to a continental ice cap than alpine glaciers do, it has not been sufficiently studied to give us so reliable a point of departure in the discussion of the subject, as the smaller glaciers. But it is so large, and departs so far from the alpine type of glacier, as to give us an enlarged idea of the dimensions which glacier ice may attain, and of the results which it may accomplish. Switzerland has an area of about 16,000 square miles. It is said to harbor 471 glaciers, 138 of which are more than four and three-fourths miles long.[1] According to official surveys, the 471 glaciers, and the snowfields associated with them, have a total area of a little more than 700 square miles. The estimated area of the ice cap of Greenland is about 300,000 square miles, an area nearly nineteen times as great as that of all Switzerland, and about 422 times as great as that of the united area of all the Swiss glaciers and snowfields.

The drift of North America is estimated to cover an area of about 4,000,000 square miles,[2] an area only a little more than thirteen times as large as the area of Greenland's ice sheet. Stated in the form of ratios, therefore, the snow and ice-covered area of Switzerland is to the snow and ice-covered area of Greenland as 1 is to 422; while the snow and ice-covered area of Greenland is to the North American area of drift as 1 to 13. The ratio between the entire snow-covered area of Switzerland and the

[1] HEIM, Handbuch der Gletscherkunde, 1885.

[2] UPHAM: Appendix to Wright's "The Ice Age in North America."

area of the ice cap of Greenland is, therefore, much greater than that between the latter and the drift-covered area of our continent. From the standpoint of ratios, it is an enormously greater jump from an alpine glacier to the ice cap of Greenland, than from the ice cap of Greenland to such an ice sheet as must have covered the northeastern part of our continent, if the drift be the product of glacier ice. If the comparison of the three areas be made without resort to ratios, their relative sizes are expressed approximately by the following numbers: 1, 422 and 5634.

But even Greenland does not possess the greatest ice sheet known. The Antarctic continent—for this land and ice mass seems to merit the name of continent—is almost completely covered with ice, so far as known. While its area has not been determined with accuracy, it has been recently estimated to contain at least 4,000,000 square miles,[1] that is, an area equal to the great sheet of drift of North America, an area twice as great as that of the drift which mantles northwestern Europe. The existence of so great an ice sheet today makes it easier to think of the existence of an equally extensive ice sheet elsewhere in the past. It removes the element of incredibility which, at first thought, seems to attach to so striking a theory as that of the glacial origin of the drift. From the standpoint of knowledge concerning ice sheets, the glacier theory is a possible theory, but it is not to be understood that the existence of an Antarctic ice sheet, equal in size to the area of North American drift, is any argument for the glacier origin of our drift. It is more difficult to account for the existence of an ice sheet in temperate than in frigid zones. But in spite of the difficulty, our study of the drift has led us to the conclusion that glacier ice was the principal agent concerned in its production.

Glaciers and Icebergs Co-operating.

Granting that glacier ice was the principal agent of the drift, may it not still be true that other agents were concerned in its production? If so, to what extent? It is well known that the

[1] Murray. Proceedings of the Royal Geographic Society. 1894.

earth's surface is subject to movement. Considerable areas are known to undergo slow elevation, while other adjacent or distant areas are suffering subsidence. If, during the drift period, glaciers formed somewhat extensively on the higher lands now covered by the drift, it might be conceived that a moderate subsidence would allow ice to float out from the glaciers of the higher lands over the waters covering the intervening lower areas, thus distributing the drift over them. That is, the drift might be thought to be the joint product of glaciers and icebergs, glaciers working on the higher lands and icebergs over the lower. Conjecturally, the relative importance of these two agents might vary greatly, but the glaciers must have remained sufficiently extensive to give rise to the ice of the icebergs. But unless it attributed the chief work to glaciers, such a combination hypothesis as this seems open to fatal objections. We have already seen what icebergs can do, and that some of their results may simulate those of glacier ice.

On the hypothesis that icebergs were an important agent in the production of the drift of the lower lands, it would be expected that the distinctively glacial marks would be absent from the lower drift-covered lands, especially near the outer borders of the drift. But this is not the fact. Marks of one sort or another which seem to be distinctively glacial, occur down to the level of the sea, near the southern border of the drift. Among such markings, the striæ on the trap rock south of Jersey City may be mentioned. At various other points too, as in Southern Illinois, at or very near the extreme margin of the drift, striæ are found beneath deposits which appear to be strictly glacial. While admitting that berg deposits may locally closely simulate those of glaciers, we cannot admit that icebergs can produce such striæ as are found near the margin of the drift at many points, even at altitudes scarcely above the level of the sea.

On the hypothesis which we are here considering, too, it would be expected that the position of the southern border of the drift was determined by icebergs, not by glacier ice. We have already seen that both the topographic relations of its terminus, as well

as its inherent character, preclude this belief. From the quantitative standpoint also, the drift border is not always such as would have been produced by icebergs. The drift is often too thick along its border and that in situations where there could have been no shore, and therefore no exceptional accumulation of berg deposits to refer it to icebergs. Like other parts of the drift, the border is made up of materials which were largely gathered close at hand. The glacier ice itself, or some agent capable of accomplishing results which have not been distinguished from those of glacier ice, reached the approximate, and often the exact southern border of the drift-covered area. Further, the character of the drift and its accompanying phenomena indicate that the same forces which were operative on the higher lands in the production of the drift, were operative on the lower also. There is not a higher body of drift of one sort, and a lower body of drift of another sort, as this hypothesis would demand.

Nevertheless, nothing which is here said precludes the idea that lakes of lesser or greater magnitude may have been associated with the ice sheet for longer or shorter periods of time at one stage and another of its development. If such lakes existed, iceberg deposits were doubtless made in them. Berg deposits were doubtless likewise made wherever the glacier ice reached the sea, and since the coastal regions may have been lower than now, it is altogether possible that some of these berg deposits were made on areas which are now land. The foregoing considerations seem only to preclude the attribution of any large part of the drift to bergs, or to floating and grounding ice.

Glaciers and pan-ice.—Any conditions which would allow of the co-operation of glaciers and icebergs, would also allow of the co-operation of pan-ice. If the coastal regions were lower than now, while ice covered that part of the drift area which was not submerged, shore ice might have been operative over a narrow belt determined by the position of the shore line. Since the shore lines must have varied with varying altitudes of the land, ice-floe and other forms of shore-ice may have operated at

one time and another over all that part of the land surface which was submerged during the drift period. If the amount of submergence during the drift period could be determined, we should have the maximum measure of the extent of the operation of pan-ice. Pan-ice might produce results closely simulating certain results produced by glacier ice. On the glacier-pan-ice combination hypothesis, too, it is possible that any region affected by pan-ice at one time may have been affected by glacier ice at an earlier time, and that the effects of the glacier ice were not wholly obliterated by the pan-ice. On the other hand it is conceivable that a zone affected by pan-ice at one time was subsequently elevated and covered by glacier ice which may have partly or even wholly obliterated the effects which the pan-ice had produced.

The results which shore and pan-ice acting alone can effect, have already been studied. That both were operative about the shores of the land which the glacier ice covered during the drift period cannot be doubted, any more than can the existence of icebergs. The question of the relative importance of pan-ice and glacier ice in the production of the drift is a question concerning which there is much difference of opinion.

Except along the coast lines and along the shores of lakes pan-ice could not have been operative. Away from the coasts, therefore, little can be ascribed to it. This removes the larger part of the drift area of the United States from the zone where shore or floating ice in any form can have been long effective. Along the southern part of the drift-covered coast of the United States there is no conclusive evidence of subsidence during the drift period. Further north, subsidence seems to have been a fact, and shore ice was doubtless a more considerable factor. It is not without significance that the Canadian geologists attribute much more importance to pan-ice than do the geologists of the United States. Some of them ascribe to it a work comparable in importance to that which the glacier ice effected.[1] But the difference in views is perhaps one of degree rather than of

[1] SIR J. WILLIAM DAWSON. The Canadian Ice Age. 1893.

kind. The glacial theory involves the co-operation of pan-ice as well as icebergs, or at least recognizes the possibility of this co-operation. At the close of the drift period the relative importance of the results of pan-ice must have depended partly on the vertical range of its activity as determined by changes of relative level of sea and land, and partly on whether the glacier ice subsequently over-rode the zone of the early activity by the pan-ice. The known facts concerning the relative changes of level of sea and land, and the known facts concerning the nature of the drift itself, seem to ascribe by far the larger part of the work involved in its production, to glacier ice. The functions of other forms of ice seem to have been very subordinate.

Significance of the abundance of stratified drift. The fact that so much of the drift is stratified has sometimes been thought to be a difficulty in the way of the glacial theory. It is certainly true that the deposits made by glaciers directly are unstratified; it is certainly true that a very considerable portion of the drift is stratified. But it is to be remembered that the ice of every extinct glacier, be the same large or small, was converted into water upon its dissolution. It is to be remembered that as the ice of any glacier moved forward during the period of its growth, it was constantly melting, so that, barring the loss by evaporation, all the ice of any glacier, from its inception throughout the whole period of its history to final dissolution, was converted into water, and that most of this water ran for longer or shorter courses over the surface of land, either beneath or beyond the ice, often modifying the surface of the drift already deposited by the ice, and often depositing upon it, in bedded form, such gravels, sands, and silt, as fell to its lot to carry and deposit. If northern North America and Europe were covered by huge ice caps, as the glacial theory of the drift supposes, every pound of these stupendous ice masses which did not evaporate was sooner or later converted into water. According to the glacial theory, therefore, the amount of water which was operative jointly with the ice in producing the drift, must have been nearly as great as that of the ice itself. It follows that the glacier theory of the drift not

only allows, but even demands, that a large part of the drift be stratified. It demands that the water issuing from the ice should carry beyond it such products of the glacial grinding as its currents were able to handle. This is exactly what is taking place in glaciers today, and the stratified valley drift extending beyond the great body of unstratified, argues that this is what took place when our drift was deposited.

In searching for the explanation of the drift, therefore, if the facts concerning the drift and its relations are before us in their fullness, it would seem that there is little room for doubtful theorizing. Geologists are now very generally agreed that glacier ice, supplemented by those other agencies which glacier ice calls into being, is the only geological agent which could have produced it. But it is here repeated that this does not preclude the belief that at various times and places, in the course of the ice period, icebergs may have been formed, or that locally and temporarily they played an important rôle. It does not preclude the idea that wherever icebergs existed, berg deposits may have been made. It does not preclude the idea that pan-ice may have been an important factor locally. It does not preclude the idea that, contemporaneously with the production of the great body of the drift by glacier ice, the sea may have been at work on some parts of the present land area, modifying the deposits made by ice and ice drainage. Indeed, there is abundant evidence that such was the fact. There is abundant evidence that in some regions now covered by drift, the land stood lower than now, or the sea higher, when the drift was deposited, or since.

The glacial theory does not deny that rivers produced by melting ice were an important factor in transporting and depositing drift, both within and without the ice-covered territory. It does not deny that lakes, formed in one way and another through the influence of the ice, were locally important in determining the character of the drift. Not only does the glacier theory deny none of these things, but it distinctly affirms that rivers, lakes, bergs, and pan-ice must have co-operated with the glacier ice, each in its appropriate way and measure. ROLLIN D. SALISBURY.